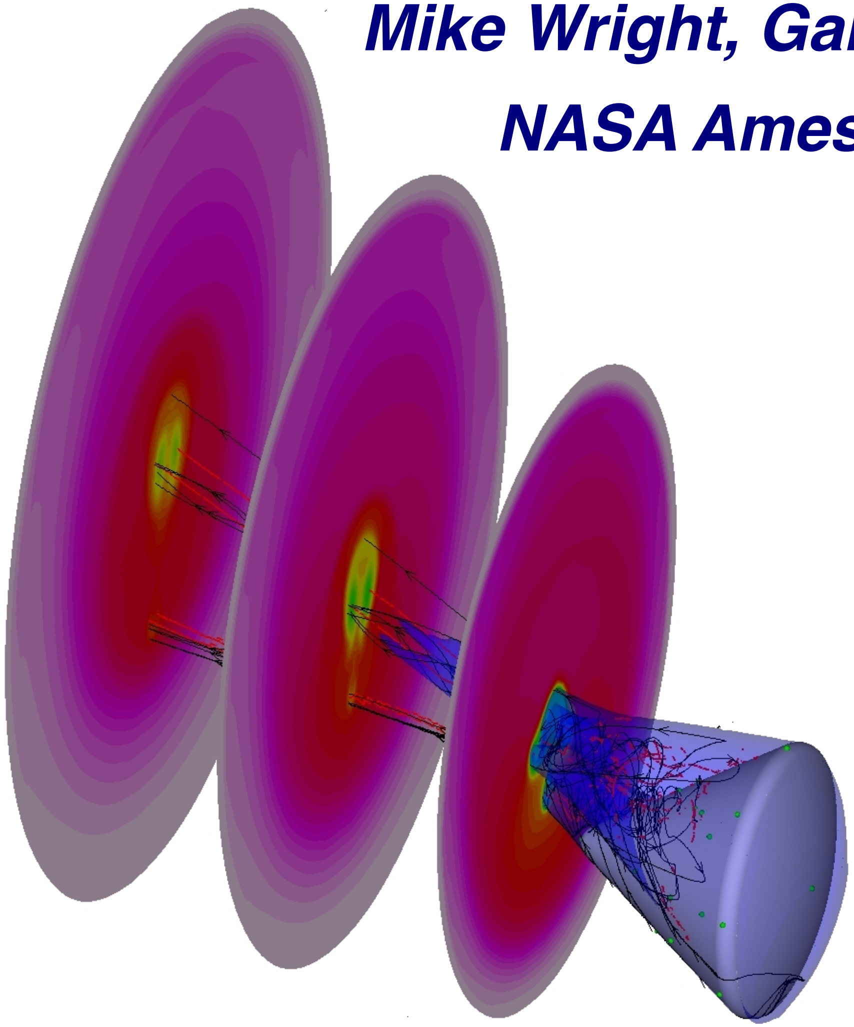
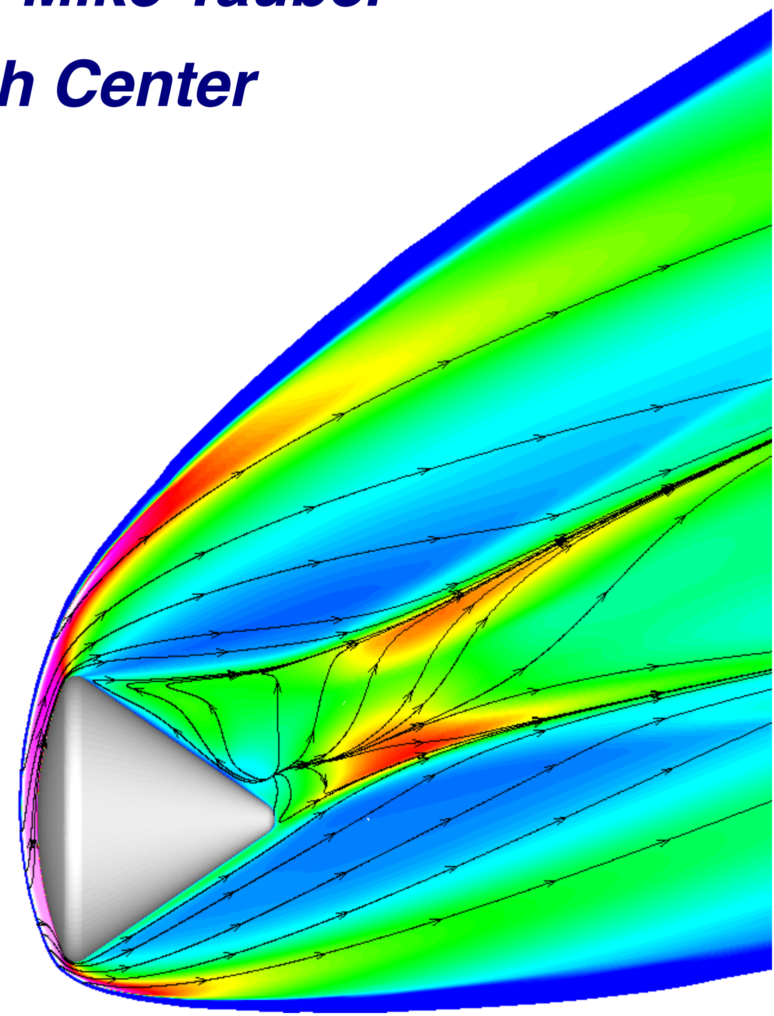
Survey of Aerothermal Modeling Needs for Future Planetary Probe Missions

Mike Wright, Gary Allen & Mike Tauber

NASA Ames Research Center





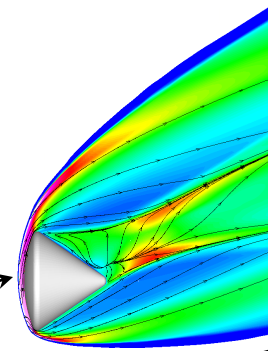
Work sponsored in part by the NASA In-Space Propulsion Program

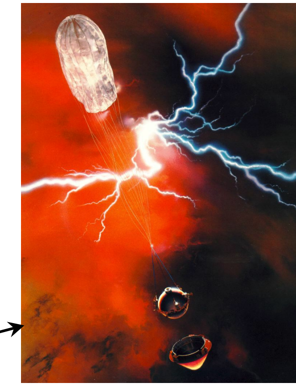
Where Have We Been?

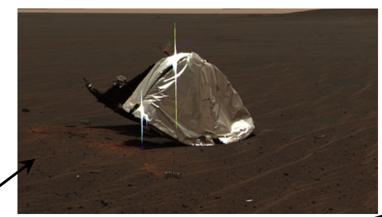
Flight	Agency	Entry Date	Destination	V (km/s)	α (deg)	Result
Venera 3	USSR	Mar. 1966	Venus	~11	0	Comm. Failure
Venera 4	USSR	Oct. 1967	Venus	~11	0	Success ♦
Apollo 4	NASA	Nov. 1967	Earth	10.7	25	Success
Mars 2	USSR	Nov. 1971	Mars	~6	0	Failure ♦
Viking I & 2	NASA	Jul/Sep. 1976	Mars	4.5	11	Success
Pioneer Venus (4 probes)	NASA	Dec. 1978	Venus	11.5	0	Success
Vega 1 & 2	USSR	Jun. 1985	Venus	11.5	0	Success
Galileo	NASA	Dec. 1995	Jupiter	47.4	0	Success
Pathfinder	NASA	Jul. 1997	Mars	7.5	0	Success
MPL	NASA	Dec. 1999	Mars		0	Rocket Failure
DS-2	NASA	Dec. 1999	Mars	6.9	0	Failure
Beagle	ESA	Dec. 2003	Mars	5.4	0	Failure
MER-A	NASA	Jan. 2004	Mars	5.6	0	Success
MER-B	NASA	Jan. 2004	Mars	5.6	0	Success
Genesis	NASA	Sep. 2004	Earth	11	0	Parachute Failure
Huygens	ESA	Jan. 2005	Titan	6.5	0	Success
Stardust	NASA	Jan. 2006	Earth	12.6	0	Success

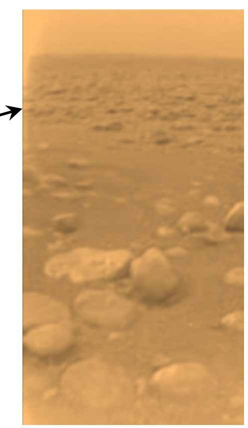
♦ 9 other successful Venus entries

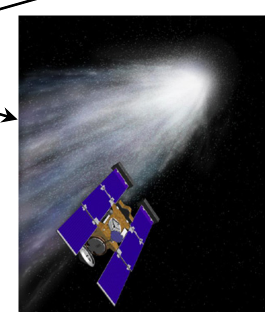
♦ 5 other failed Mars entries



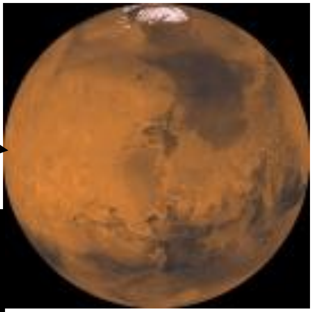






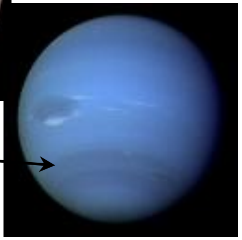


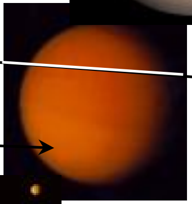
Where Are We Going?

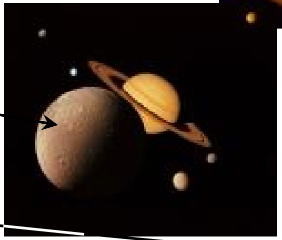


➢ Active Mars Exploration Program

- Launch opportunities every two years
- Scheduled: Phoenix (2007), MSL (2009), Scout AO (2011)





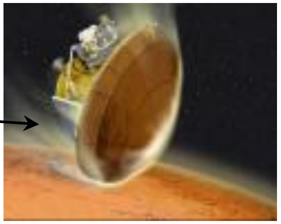


➢ Solar System Exploration (Decadal Survey)

- Jupiter Polar Probes
- Neptune Probes
- Return to Venus
- Lunar/Comet/Asteroid Sample Return
- Titan Exploration (rovers, balloons, airplanes)
- Saturn Probes?

➢ Vision for Space Exploration

- Return to the Moon (CEV), eventually to Mars
- Emphasis on technology demonstration, human precursor missions



➢ Aerocapture as a Propulsion Alternative

- Use aerodynamic deceleration in lieu of propellant to capture into orbit
- Significant mass savings are possible for many destinations

Why is Aerothermal Modeling Important?

- **Heat flux (with pressure & shear) used to select TPS material**
- **Heat load determines TPS thickness**

Can't we just 'cover up' uncertainties in aerothermal modeling with increased TPS margins?

- **Sometimes, <u>but</u>:**
  - Margin increases mass; ripple effect throughout system
  - Without a good understanding of the environment risk cannot be *quantified*; benefits of TPS margin cannot be traded with other risk reduction strategies
  - Margin cannot retire risk of exceeding performance limits
  - For some missions (i.e. Neptune aerocapture, Jupiter polar probe), improved aerothermal models may be *enabling*

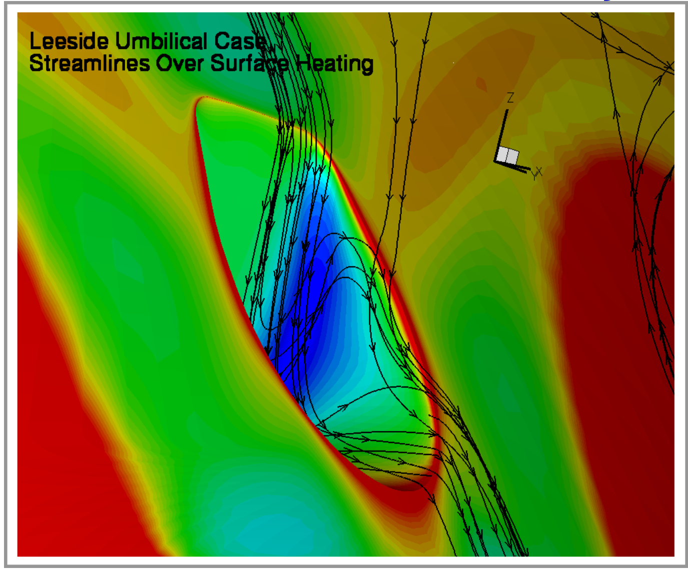
Can't we retire all uncertainties via testing?

- **No!:**
  - No ground test can simultaneously reproduce all aspects of the flight environment. A good understanding of the underlying physics is *required* to trace ground test results to flight.
  - Flight testing too expensive for anything other than final model validation

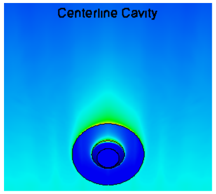
CFD Process for Planetary Probe Design

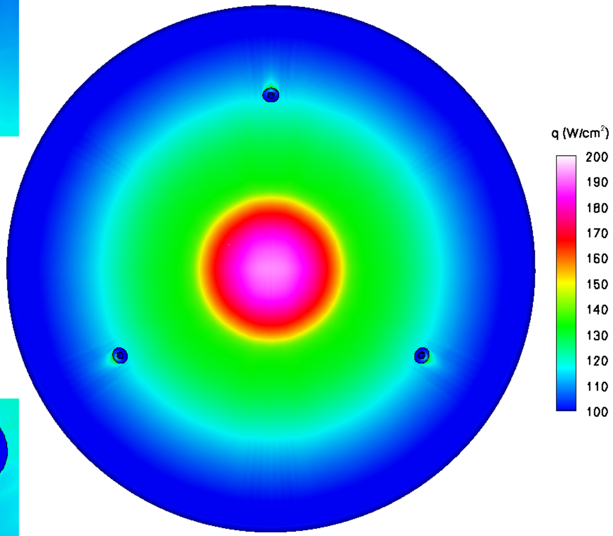
- **Advances in parallel computing, efficient implicit algorithms have enabled rapid turnaround capability for complex geometries**
  - Full three dimensional CFD is an integral part of all planetary probe TPS design
- **Modeling gaps are physics driven; mission specific**
  - Physical models employed are by and large based on 20-30 year old methodologies

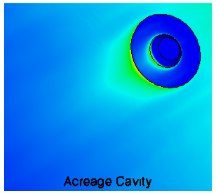
Mars Phoenix Umbilical Cavity



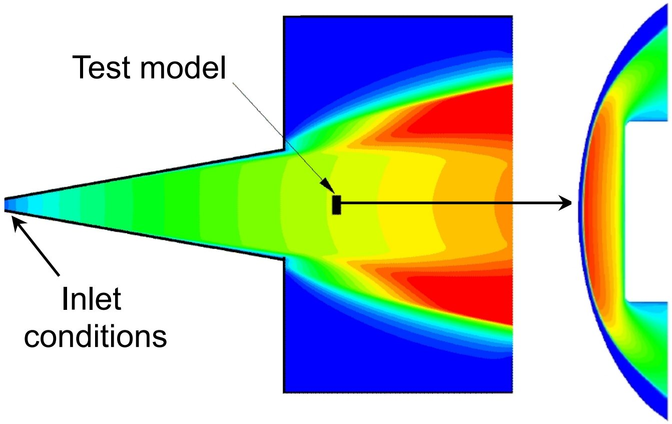
Genesis Penetration Analysis

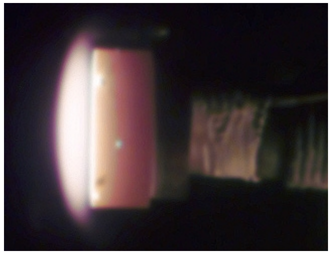






Arc Jet Model Simulation





Nozzle flow CFD simulation **Model CFD simulation** **Arc jet test**

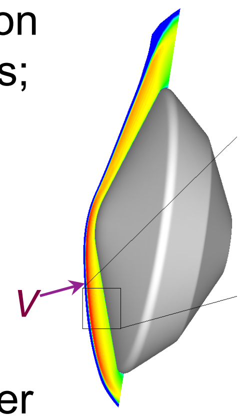
Aerothermal Modeling Needs

- **Reacting Flow Physics**
- **Radiative Heating**
- **Transition and Turbulence**
- **Coupling Effects**
- **Afterbody Heating**
- **Unsteady Separated Flows**

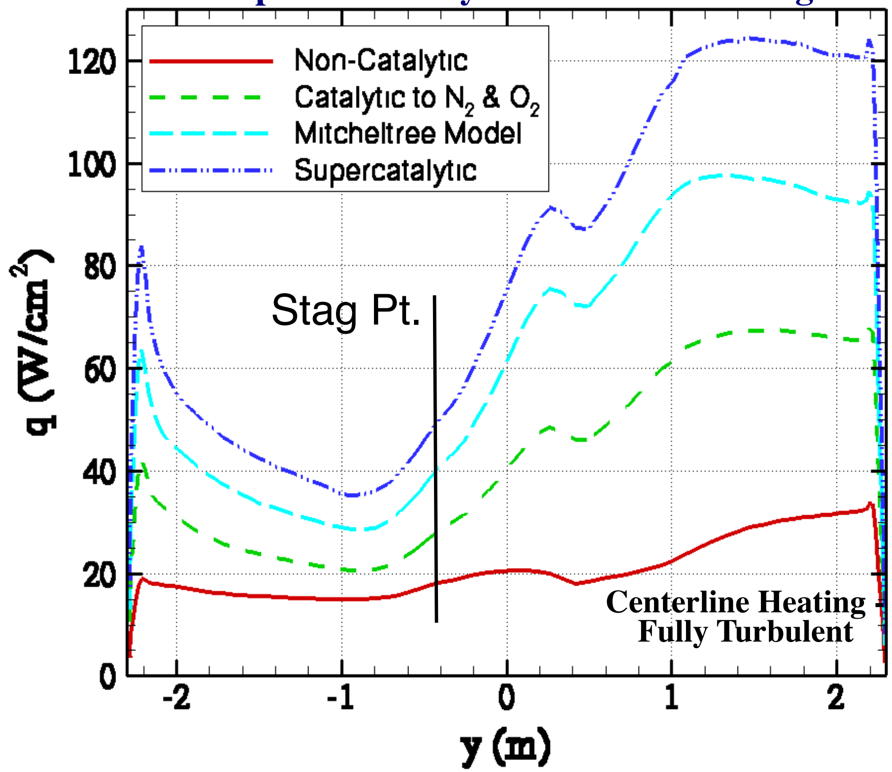
Reacting Gas Flow Physics
Current Status and Identified Gaps

➢ **Chemical Kinetics and Thermal Nonequilibrium Models**
- developed for Earth entries; applied other destinations with minimal validation
- developed for low ionization levels; applicability for fast entries (e.g. giant planets) not well known

➢ **Surface Kinetics**
- catalysis and surface recession have a huge effect on heat transfer
- validated models for non-Earth entries do not exist; bounding (possibly very conservative) models are employed



Mars Science Laboratory - Impact of Catalysis Model on Heating



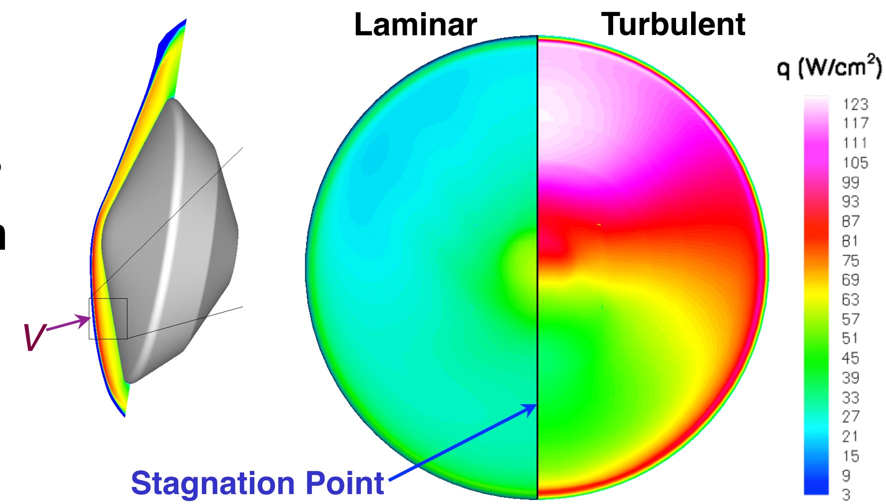
➲ **Models are required for all of these processes to accurately predict net heat transfer**

Turbulent Heating and Transition
Status and Remaining Gaps

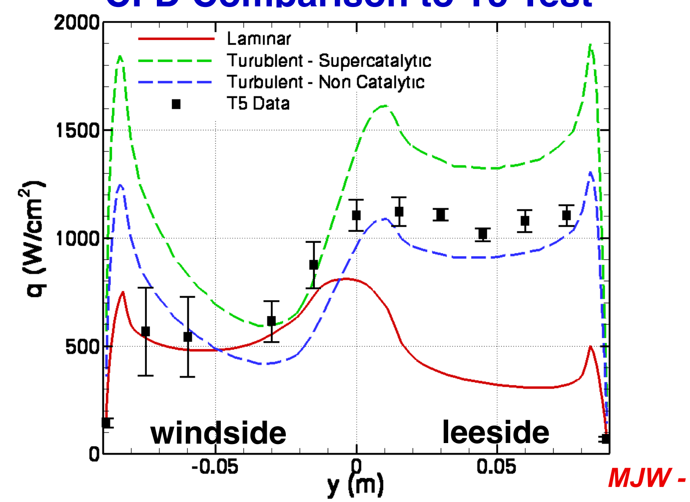
- **Leeside turbulent heating recently identified as an issue for lifting blunt cones**
  - current uncertainty > 50%, poorly defined
- **Other turbulence mechanisms become important for mid to high L/D geometries**
- **Blowing/roughness dominated transition will be crucial for ablative TPS systems**
  - models are configuration/material dependent
  - existing models require validation

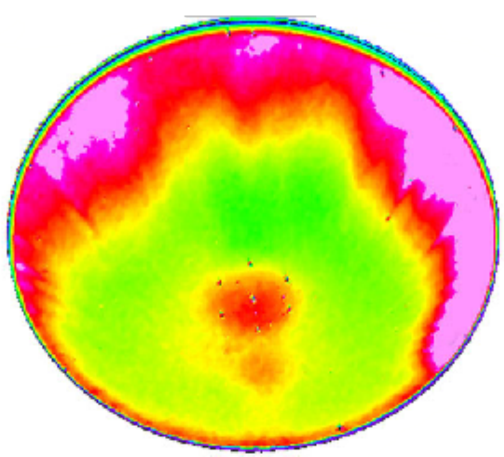
➲ **Turbulent heating remains a design driver for large entry systems**
  - No flight validation for non-Earth entries

Mars Science Laboratory
Peak Heating Condition



CFD Comparison to T5 Test





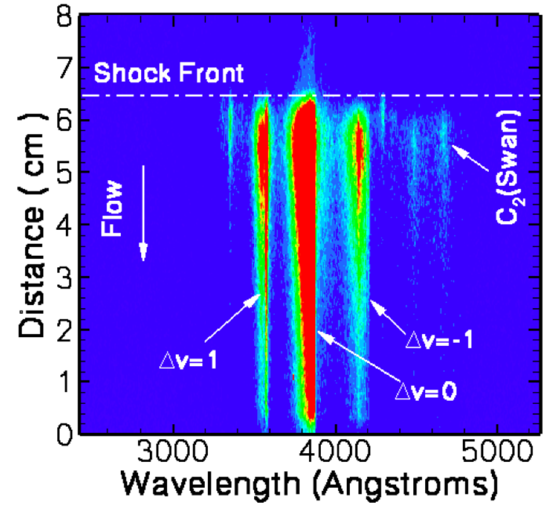
Transition in LaRC Mach 6 Tunnel

Radiative Heating
Status and Remaining Gaps

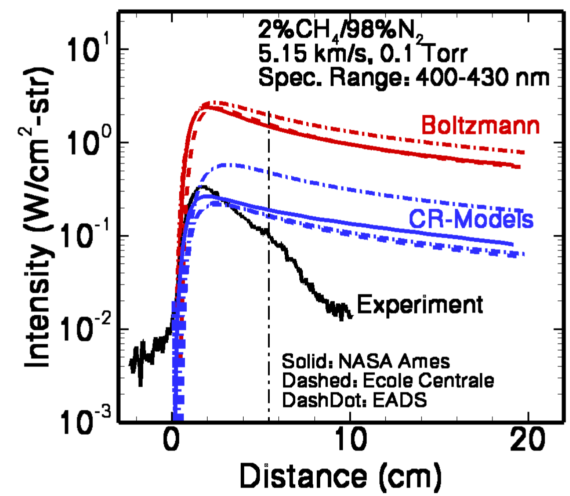
- **Radiative heating predictions have the highest uncertainties of all heating modes**
  - analysis predicts that radiation will dominate aeroheating for Titan, outer planets, and large vehicles at Venus & Mars
  - radiation can be strongly coupled to flowfield
  - detailed models exist only for Earth
- **Huygens entry spurred interest in Titan radiation**
  - several models in literature; Titan probably better understood than all solar system targets other than Earth
  - additional work is required to reduce remaining uncertainties
- **Shock tube data used to improve existing models**
  - recent testing performed for Titan (ISP, 2004), Mars (ISP, 2006), and Earth (CEV, 2006)
  - results for planetary bodies to be discussed at workshop in Sep.
- **No non-Earth flight data exist**
  - Huygens carried no heatshield instrumentation
  - Galileo, PV data insufficient to determine radiative heating levels

➲ **Collisional-radiative models are required for all planets**

Sample EAST Dataset



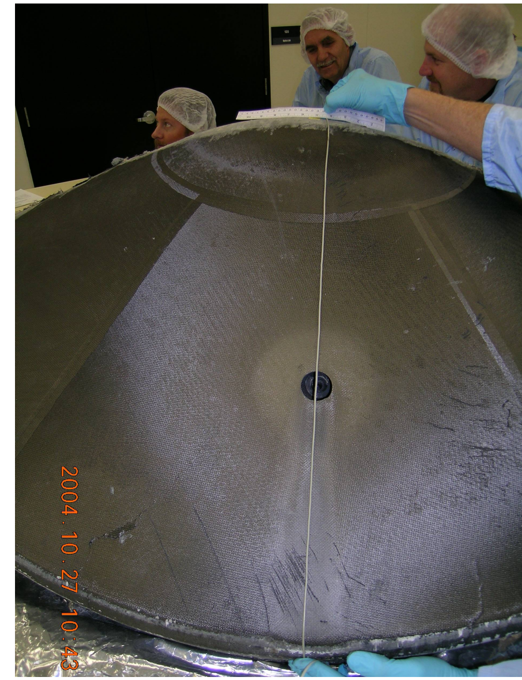
CN Radiation Model Validation



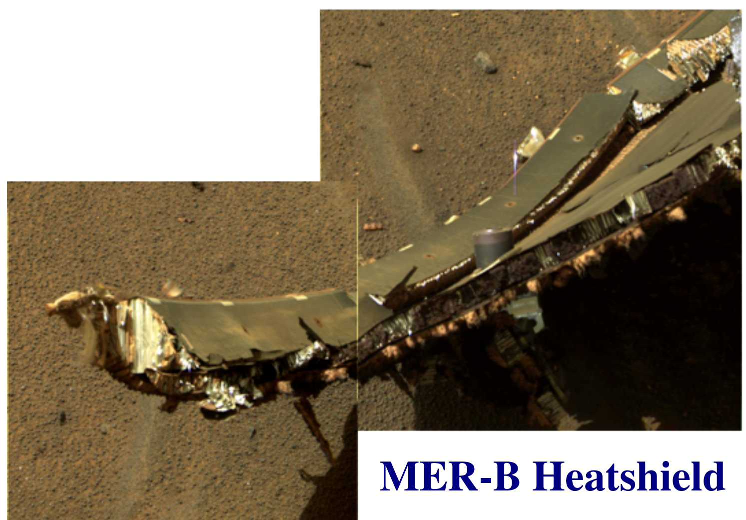
Final Model Validation:
Flight Data and Recovered Hardware

- **Instrumenting science missions is the best way to obtain model validation data for follow on probes**
  - Recent trend away from heat shield instrumentation must be reversed; next opportunity is MSL (2009)
- **In flight observation (e.g. Stardust) can be valuable, but only possible at Earth**
- **Post-flight hardware inspection can be useful for model deficiency identification (e.g. Apollo coking)**
  - Hardware recovery can be difficult to impossible
  - Cannot give temporal information

Genesis Heatshield



Stardust Airborne Observation



MER-B Heatshield

Stardust Capsule

Conclusions and Recommendations

- **Most of our aerothermal models were developed for Earth and applied to other destinations with minimal validation**
- **Challenging destinations include all gas giants, Venus and large payloads at Mars**
- **Three major priorities show up across multiple destinations**
  - Shock layer radiation, including coupling effects
  - Turbulent heating and transition
  - Gas-surface interaction, including catalysis
- **Improvements to aerothermal models will have a significant payoff in terms of entry risk quantification and system mass savings**
  - Better understanding of entry risks will enable more informed system trades
  - Aerothermal model improvements may enable a new generation of ambitious science missions
- **Flight data are required to validate models for non-Earth entries**
  - Much can be gained by instrumenting science missions

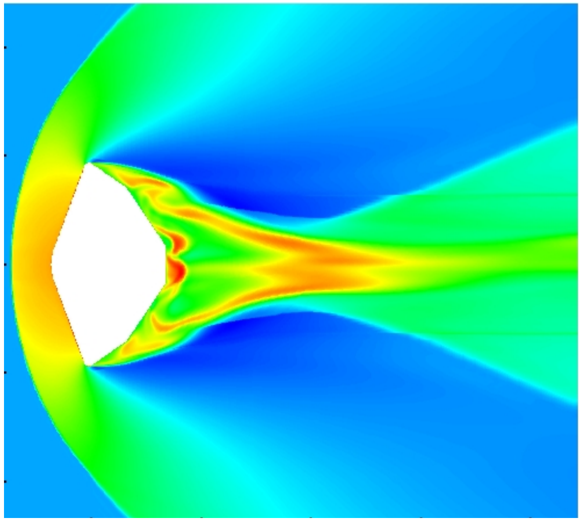
Backup

Afterbody Heating
Status and Remaining Gaps

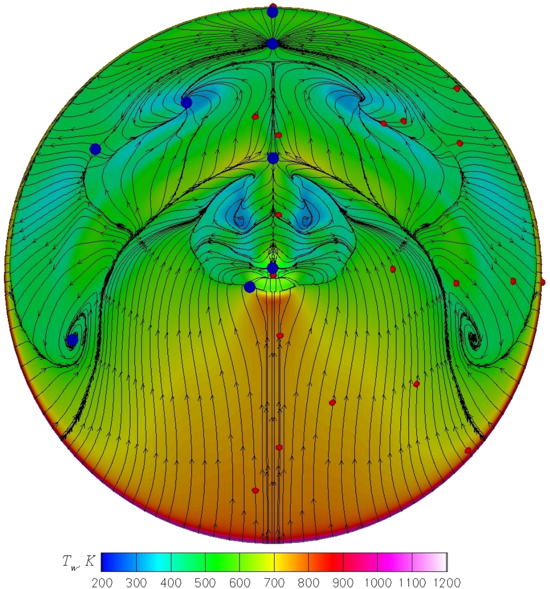
- **Current uncertainty levels assumed 50-300%**
  - Impacts backshell TPS selection and mass
- **Physics drivers include turbulence, unsteadiness, rarefaction, and RCS interaction effects**
- **Limited validation with flight data for Earth (Apollo) and Mars (Venus) entries**
  - Good agreement with Earth data, CFD significantly underpredicts Viking heating

➲ **More work required for the range of entry missions**
  - non-Earth destinations
  - open backshells (fluid-payload interactions)

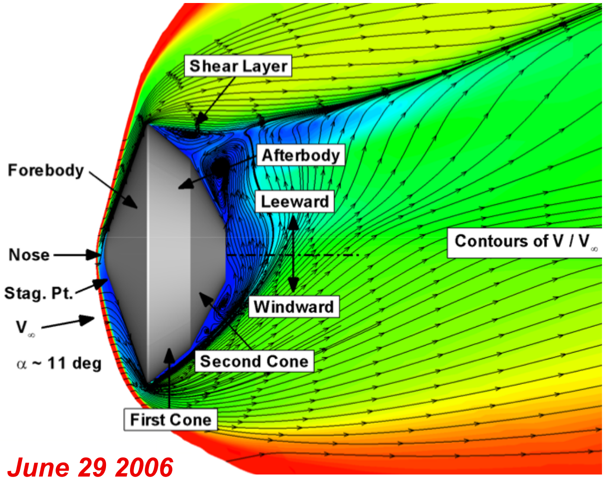
DES Simulation of Titan Wake

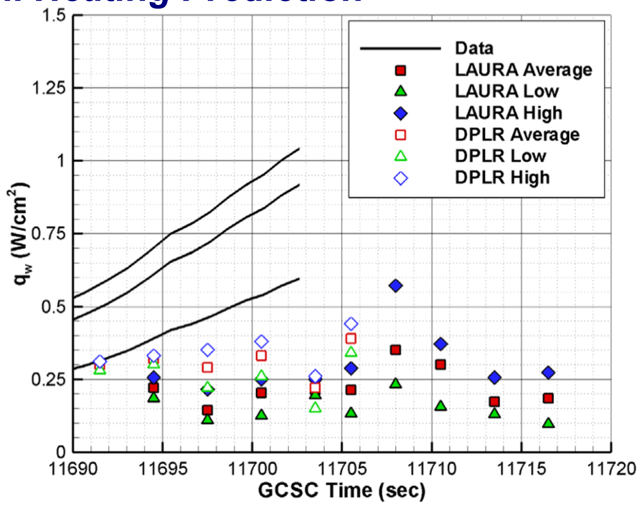


AS-202 Backshell Oilflow



Viking Aftshell Heating Prediction





Flowfield/Radiation/Ablation Coupling

Status and Identified Gaps

- **Coupling can have a major impact on net heating and ablation rates**
- **Loosely coupled radiation methodology has been demonstrated**
  - Stardust design, Fire-II post-flight analysis
  - Intractable for strongly coupled flows (outer planets, Venus)
- **Ablation coupling models under development**
  - Ablation product blockage of radiation is not well characterized
  - Required rates are material and environment dependent; most not known

➲ **For this type of environment, coupled solutions are *required* to obtain reasonable aeroheating predictions and to make informed TPS decisions**

Titan Aerocapture Radiative Heating